ORIGIN AND DYNAMIC OF THE TANK OUTBURST OF AN OIL-FILLED TRANSFORMER

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Abstract

The paper refers to an event occurred inside an electric substation, happened at the restoration of the electrical supply of an oil-filled transformer subsequent to an intervention of periodic maintenance, and consisting of the outburst of the oil tank with leaking of the diathermic oil both as a high temperature vapor and as liquid on fire. The development of the case study we focus on shows the event chain rebuilt with high reliability and proposes the adoption of preventive measures for the safety of the workers.

Keywords: *oil-filled electrical power transformer, electrical arc, temperature increase, pyrolysis gases, pressure increase, elasto-plastic deformation of the casing, irrelevance of oil maintenance on overpressure*

1. INTRODUCTION

It is known from the technical literature that inside the tank of an electrical transformer, several malfunctions of various kinds can arise suddenly.

One of the most common causes is constituted by the stroke of an electrical arc inside the machine; this is due to two types of events: breakage of components for defects and age, or loss of dielectric strength between the points through which the arc is struck.

The effect of the arc is to increase instantaneously the oil temperature (along the line of arc) up to trigger the pyrolysis reaction, that is the cleavage of the oil in various gaseous hydrocarbons, mainly hydrogen and acetylene, with small fractions of methane and ethylene, and also a part of carbon in the solid state. This reaction leads to the rapid development of a gas bubble composed of the aforesaid pyrolysis gases at high temperature (local and instantaneous measured temperatures can reach several thousand degrees, but relatively to the development of the gases of pyrolysis, the literature refers temperatures close to 2000 ° C) , which causes the formation of a sudden increase of pressure, which, in the form of a wave, propagates inside the transformer.

The medium of propagation of this wave is the oil liquid that fills the container (tank) which contains the windings; the propagation of the wave takes place at a speed that depends on the state of the oil: when the wave reaches the walls urges them mechanically in a way that can be so intense as to lead, often, to structural failure of the tank or the opening of covers for mechanical deformation.

The speed of propagation of the pressure wave is very high and it is that characteristic of the propagation in liquid media (about 1000-1500 m/s).

It may be useful to note that if in the oil are dissolved percentages of gas existing at the stroke of the arc, this speed greatly decreases making the phenomenon of propagation of the pressure wave less impulsive and less traumatic for the mechanical structure.

The pressure wave, therefore, slows down in its movement as it increases the density of the gaseous component which dampens the dynamic effects: at percentage of only 10% by volume of dissolved gaseous species in a liquid, the speed is lowered already to the one typical of a gas (a few hundreds of m/s).

As the phenomenon of propagation is, in any case, very fast (order of 10^{-4} ms, depending, as mentioned, on the state of oil and gas dissolved in it), the calculation for this pressure is the resultant of dynamic

phenomena still very rapid (much more rapid the duration of the electrical arc which generates the same wave, order of 10^{-3} ms) and complex, which instantly reported to the mechanical structure the task of the reaction pressure to the phenomenon: in essence, it is as if instantly pressure that is generated locally following the development of the gas bubble, could reach the internal surfaces of the container.

Being able to neglect the propagation phenomenon (since fast and over neglectable distances) the discussion can follow, in a process of simplification reasoned, an approach that is defined in engineering as quasi-stationary: the mechanical behavior of the container (i.e. its elasticity) cannot be overlooked and contributes to define in a marked pressure inside the transformer.

Literature references introduce some coefficients, but of little influence, that increase the pressure value which is calculated as a result of a calculation quasi-stationary thus taking into account unsteady phenomena (dynamic) connected to the first instants of formation of the gas bubble. From what has been argued so far, the result of an extensive theoretical and experimental literature, which was later referred, it is clear that basing the calculation of the pressure (impulsive) assuming that the container is infinitely hard it would be a serious mistake. In this case the behavior of the container would be erroneously assimilated to that of hydraulic and oil-dynamic cylinders.

The oil compressibility, which plays large part in the calculation of the excess pressure resulting electrical arc, should be absolutely integrated with another property that is the deformability of the tank of the transformer, definable also as elasto-plastic pliability of the containment structure: the pressure wave, in fact, reaching the container deforms and, so doing, expands the volume available for oil and dissolved gaseous species, contributing to the rapid decreasing of pressure. So much so that, deliberately, the containers of the transformers in the design stage are provided able to deform with controlled deformation.

The mechanical deformation of the container makes the calculation of pressure more complex, but certainly more responsive to the real situation and leads to overpressure values much lower and not related with the initial content of dissolved gases in the oil in relation to its aging. Due to the structural failure of the container of the transformer or rather the opening parts of the cover, as it was in the case study in object for mechanical deformation, liquid oil, oil aerosols and gases generated by pyrolysis ("explosion" source) are violently released by pneumatic effect. The literature refers to two different accident-scenarios, interdependent:

1) ignition of the liquid phase of the oil spewing from the case: *pool fire* scenario;
2) ignition of gas cloud made with oil mist and gaseous products of pyrolysis, mixed with air: *secondary explosion* scenario.

In fact, for less intense phenomena, the complete scenario of pool fire, which is the most frequent, may not happen necessarily, being replaced by a sudden escape of oil at high temperature which may not even be the subject of a macroscopic combustion, remaining in the liquid state. This happens mainly when the oil leakage is most frequently caused by a loss of both flanges (lids) and/or from the gash in the form of irregular openings of the tank itself (without prejudice to the overall structure of the transformer): in such cases, it produces a release for pneumatic effect of jets of oil very substantial and fast, able to break up into drops or clouds, which can promote partial combustions or further temperature increases, in relation to the high oxidation capacity of the drops in suspension in the air, compared to those of jets solid. It should be added that there are currently no prediction tools able to establish with accuracy, in function of the energy of an accident and the geometrical conditions of the transformer, which is the spatial distribution of the release of oil, its nebulization, its ignition power: the technical literature is based on incidental observations occurred in the various cases that still carry out a case study, and preliminary theoretical approaches that have had the experimental confirmation needed to be considered provisional.

Another key consideration emerges from the analysis carried out and from what the specific literature of the sector refers: the electrical arc that is generated has had a power classifiable as high (10 MW) for the power class of the transformer concerned and the energy released is also definable as high, in relation to the ability to develop a gas bubble (about 220 liters, i.e. a quarter of the volume represented by the

whole container) also quantitatively significant. Such a phenomenon is of sufficient magnitude to let think of a specific event, abnormal and unpredictable, with high probability caused by external factors not related to the daily operation of the transformer in which, over time, although there is a continuous degeneration of oil respect to dielectric properties: these factors are certainly able to cause arc or partial electrical discharges, but not at the intensity manifested in this event, with electric power circuit interruption. Moreover, the normal degeneration of the oil is also the result of micro-discharges that inevitably are present inside of transformers and that do not affect the operation.

2. PRESSURE INCREASING MODEL

The problem of the electrical arc, in oil-insulated power transformers, has already been the subject of various investigations both experimental and numerical. It is certainly useful to have an experimental knowledge of the pressure phenomena (the order of magnitude of overpressure) and of the influence of the dynamic phenomena in support of the goodness of the hypothesis of quasi-stationary nature of the phenomenon and the importance of the elastic-plastic mechanical behavior of the transformer container. Experimental data detected by pressure transducers in the points near the electrical arc and in some points inside the tank, until the walls of the casing of the transformer, have been measured with accuracy and show [13, 14, 15, 16, 17] in unequivocally the relationship between the pressure peak (near the arc), and those that stimulate the body according to a quasi-stationary model (which takes into account the deformation of the transformer). It is evident that this approximation is as close with good precision to the state of stress instantaneous pressure, albeit with minor corrections. This effect was observed already in the 80s by [5] which suggested introducing a multiplicative factor on the pressure by 1.3 times (30% increase) to 1.6 times (increase of 60%) to take into account the dynamic effects, compared to the case quasi-stationary. This result was most recently reiterated in a more precise and accurate way in [13, 14, 15, 21] and, more recently, [16, 17] where more accurate measurements of the pressures inside the casing of the transformer show instantaneous pressure peaks that does not exceed 8-10 bars in the most extreme conditions, for pressure values quasi-stationary which are lower by 20-40%. The consideration of the deformation of the body has to be considered next to a careful definition of the variables involved in the process of pressurization; especially compared to the phenomenon of pyrolysis that cannot be treated as a vaporization oil equivalent as a result of injection of energy produced by the arc.

2.1 Pressure calculation model

2.1.1 Energy released during the electrical arc exploiting

The first data necessary for the quantification of the effects of the “explosion” and fire scenarios in a transformer regards the calculation of the energy associated to the electrical arc, to which the amount of gaseous products of pyrolysis reaction is related. Taking a reference value of 10 MW and with a time interval of event of 220 · 10-3 s provides, with power supposed constant during the exploiting of the arc, an 'energy released by the arc of 2,200 kJ. This value, despite the uncertainty of the phenomenon, seems to be acceptable and highlights, compared to the power transformer, the manifestation of a phenomenon of high intensity.

2.1.2 Free gas volume generated due to the arc manifestation

The energy of the arc (in relation to the high instantaneous power would) causes a rapid and intense rise of temperature along the arc and this causes pyrolysis of the oil invested by the discharge. The pyrolysis process may be described chemically by the chemical reaction:

$$C_{10}H_{22} = 10.6 \cdot H_2 + 0.06 \cdot CH_4 + 0.23 \cdot C_2H_2 + 0.02 \cdot C_2H_4 + 9.43 \cdot C \quad (1)$$

that is not to be confused with a process of vaporization of the oil. The pyrolysis process, in fact, is a chemical reaction whereby a species (the oil), it splits into other species (pyrolysis gases) that have other chemical composition and other properties that are not those of the oil vaporized at high temperature. If we don’t consider the pyrolysis, but the process of vaporization of the oil, the bulk of oil generated would be evaluated as the ratio between the energy released during the period and the heat of

vaporization of the oil, as if the formation of the pyrolysis gas was the effect of vaporization and not the result of a chemical reaction, which is that given in the above equation.

This process would disregard the oil warming up to the temperature of pyrolysis and, above all, the energy developed by the arc that does not participate in the pyrolysis process, creating energy losses (aspects briefly discussed below). The first term, in fact, is significant in that the pyrolysis temperature is much higher than the assumable vaporization, being of the order of 2,000 °C (local temperatures and snapshots are even more possible).

Another input that we need to determine is the molecular weight (mass) of the pyrolysis gas, assumed to be equal to 40 g/Mole. This quantity, in fact, can be calculated without the need for other references from the underlying equation:

$$PM_{pyrolisis\ gas} = \frac{M_{pyrolisis\ gas}}{V} = \frac{10.60 \times 2 + 0.06 \times 16 + 0.23 \times 26 + 0.02 \times 28}{10.91} = 2.63\ \frac{g}{mol} \quad (2)$$

the carbon being present in the stoichiometric relationship in the solid state. The low value that is obtained is justified by the high mass content of hydrogen in the pyrolysis gas which has a molecular mass equal to 2. In an attempt to give a description of the events that occurred more corresponding to reality, the calculation of the pressure that most likely was generated inside the transformer is conducted here in the most correct way by resorting to the treatments proposed in the technical scientific literature. In order to allow, even in the context of a simplified model, further predictive capability, the model has been further developed to account for the effect of the nature and quality of the oil.

An important first step is the calculation of the volume of the pyrolysis gas which is generated after the event arc. As it is well known from the literature, the phenomenon of pyrolysis produces a breakage of the molecular bonds that realize a decomposition (thermal effect) of substances reagents and their re-aggregation (or decomposition) in components molecularly simpler, as it is evident from the chemical reaction previously reported and indicated as equation.

The chemical reaction (1) was the subject of numerous studies [1, 2, 39, 18, 19] and is characterized by a significant increase in the number of moles and, therefore, by the tendency to a substantial volumetric expansion (in not confined conditions) or by a considerable rise in pressure (in confined conditions).

The calculation of gas products is a source of inherent uncertainty (oil composition, aging, energy of arc voltage, arc length and its geometry prevalent, etc.) and require that the tight reference to the specific literature of the sector that reports, average, data from numerous experiences and situations.

Specific data can be detected, for example, in [19]. The studies have made it possible to characterize the mixture of gases produced by the pyrolysis reaction in terms of concentration of the various gaseous species, the variation of some typical parameters such as the effective value of the short-circuit current (1-5 kA), the duration of the arc (0.06 s 0.18-s - that is, values of the order of 6-8 hundredths of a second -, then the next interval of 220 ms - corresponds to 22 hundredths of a second - about the event actually occurred), the distance between the electrodes (10 mm up to 40 mm significantly next to the real case in question). Even the maximum amounts of power injected during the observations are next (10.5 MW) to those that characterized the accidental event. Average percentages by volume of the main gaseous species produced, so as to assume the characteristics of the pyrolysis reaction, are the following: Hydrogen H2 = 67.7%; Methane CH4 = 9.5%; Ethylene C2H4 = 6.5%; Acetylene C2H2 = 16.2%. About the volume of the gases that are produced, the technical and scientific literature follows the approach to correlate it with energy and with the currents of arc. The subject is treated by identifying a defined volume of gas generated - in liters - (in normal conditions) per unit of energy of arc - expressed in kJ -: this is called “rate of gas products” (per unit of energy arc).

For low currents (of the order of 1 kA) said rate is of the order of 0.05 l / kJ*arc [6, 19, 20]. For current values higher than the rate in question assumes values close to 0.1 l / kJ*arco [20]. For currents still greater and typical network fault the rate is close to 0.2 l / kJ*arco [22, 23, 24, 25]. Still higher values were observed for situations of high severity up to 0.5 l / kJ*arco, [5, 21] that relate supply voltages 30-

40 times higher than those of the case (6,000 V). Approximately the temperature of the pyrolysis gas, a good reference value, as said, is equal to 2,000 ° C.

The significant change is observed in the values of the rate of gas is due to several non-recurring factors during the experiments. For the values of arc current characteristic of the event in question, in this Report we have considered three rates, respectively: 0.05 l / kJ*arc, 0.1 l / kJ*arc and 0.2 l / kJ*arc.

The technical scientific literature has suggested the value of 0.1 l / kJ*arc: the field was purposely extended to represent a large margin of uncertainty. Note the energy released during the electrical arc, the one that triggers the reaction (1) can be significantly different (obviously lower). Energy losses mean that not all the energy of the arc participating in the pyrolysis process, as well as an energy analysis must also consider other processes, that before the report (1), allow its occurrence. In addition, if reference is made to the reaction (1) there is an upper limit (theoretical) to the production rate of the gas, which can be determined by observing the various energy terms involved in (1). This calculation adds a further justification to the variability of the rate.

The energy released over the arc, indicated by "Ea", in fact, is distributed on three contributions:

$$E_a = E_1 + E_2 + E_3 \tag{3}$$

In the above relation (3):

- "E_a" is the energy fed into the system as energy arc;
- "E_1" is the heat required to raise the temperature of the oil to the pyrolysis temperature;
- "E_2" is the enthalpy of reaction of the pyrolysis reaction (absorbed by the reaction);
- "E_3" it is the dissipated energy (radiation, heat and ionization of gaseous products or other physical) or lost for processing pyrolysis.

As regards the term "E_1", assuming for the mineral oil a specific heat of 416 J/(mole $_{oil}$ · K) and a temperature difference of 2000 °K is obtained a value equal to:

$$E_1 \cong 416 \times 2000 = 832 \frac{kJ}{mol_{oil}} \tag{4}$$

As regards the term "E_2", considering the stoichiometric coefficients and the molar enthalpies of formation of the products of the pyrolysis oil and reported in the table given below (Table 1), you are obtained as follows:

$$E_2 = 350 \frac{kJ}{mol_{oil}} \tag{5}$$

	Stoichiometric coefficient	**Molar enthalpy of formation**	**Molar enthalpy of reaction**
	($_n$)	J/kmol	J/kmol
H_2	10.6	0	0
CH_4	0.0631	$-7.19 \cdot 10^7$	$-4.54 \cdot 10^6$
C_2H_2	0.231	$2.26 \cdot 10^8$	$5.22 \cdot 10^7$
C_2H_4	0.0223	$5.25 \cdot 10^7$	$1.17 \cdot 10^6$
$C_{(lampblack)}$	9.43	0	0
$C_{10}H_{22\ (mineral\ oil)}$	1.00	$3.01 \cdot 10^8$	$3.01 \cdot 10^8$
TOTAL			$3.50 \cdot 10^8$

Table 1. Table of stoichiometric coefficients and molar enthalpy values of the reaction

Whereas a mole of oil produces, as a result of the pyrolysis process, 10,91 moles of gaseous products, stoichiometric equation of the process - equation (3) - it follows that the same energy of pyrolysis may be referred to one mole of gas produced by:

$$E_2 = \frac{350}{10.91} = 32 \ \frac{kJ}{mol_{pyrolisis\ gas}} \tag{6}$$

The theoretical rate of production of gas "ν", expressed in kmol/kJ, it is therefore:

$$\nu = \frac{1}{32 \cdot 10^6} = 3.12 \cdot 10^{-8} \ \frac{kmol_{pyrolisis\ gas}}{J} \tag{7}$$

Since, in normal conditions (0 °C, 100 kPa), the volume of one mole of about 22.4 liters, it is obtained a theoretical rate, expressed in l/kJ, equal to "ν_L":

$$\nu_L = \ 3.12 \cdot 10^{-8} \cdot 10^3 \cdot 22.4 \cdot 10^3 = 0.7 \ \frac{l_{pyrolisis\ gas}}{kJ_{pyrolisis}} \tag{8}$$

to be referred to the portion of energy that participates in the process of pyrolysis. The two processes of heating oil at the temperature of pyrolysis and that of the pyrolysis reaction itself require an energy contribution equal to:

$$E_1 + E_2 = \ 1180 \ \frac{kJ}{mol_{oil}} \tag{9}$$

We can, therefore, affirm that the portion of energy that is consumed by the pyrolysis reaction (E_2/E_a) is, therefore, less than 0.296. Assuming this value as limit, the maximum theoretical rate expressed in l/kJ*arc and reported to the energy of arc (in case there are no leaks, other energy absorptions such irradiations towards the oil, the casing, etc.) is equal to:

$$\nu_L = \ 0.7 \cdot 0.296 = 0.207 \ \frac{l_{pyrolisis\ gas}}{kJ_{arc}} \tag{10}$$

The term "E_3", which encompasses all other components of energy absorbed by other physical phenomena, first among them the energy transmitted by radiation from the arc to the oil and the housing component, is difficult to determine. Loss factors of 50%, used to convey the relationship "γ" between "E_3" and "E_a".

$$\gamma = \frac{E_3}{E_a} \tag{11}$$

equal up to 0.5. Therefore, the value of the rate equal to 0.1035 l/kJ*arc, reported by numerous experimental results could also be the result of a reduction of 50% of that of the theoretical rate, being the energy concerned at the pyrolysis similarly reduced compared to the value provided from the arc. Assuming this value as a reference, noting that the energy of the arc more likely an incidental event is equal to 2200 kJ, one can calculate a volume of gas produced in normal conditions equal to:

$$V_{pyrolisis\ gas} = \ 0.1035 \cdot 2200 = 227.7 \ l \tag{12}$$

This data, which must be held very close to the reality of facts as derived using methods of literature accredited by a series of analysis and specific studies, produces an estimate of the mass of pyrolysis gas that has formed, assessable by:

$$M_{pyrolisis\ gas} = \frac{227}{22.4} \ PM_{pyrolisis\ gas} = \frac{227}{22.4} \cdot 2.63 = 26.65 \ g \tag{13}$$

The mass of oil that was in the pyrolysis process can therefore be evaluated by:

$$M_{oil} = \frac{227}{22.4} \cdot \frac{1}{10.91} \ PM_{oil} = \frac{227}{22.4} \ PM_{oil} = \frac{227}{22.4} \cdot 144 = 133 \ g \tag{14}$$

In order to properly evaluate the mechanical effects on the tank of a transformer due to the triggering of an internal arc, you must first be able to describe the dynamic behavior of the "bubble" arising as a result of pyrolysis oil. As already observed, the calculation of the pressure generated within the transformer in a case of quasi-stationarity of the process (as noted previously) requires:

a) the assessment of the volume of gas that forms as a result of the event of arc;

b) the determination of a pressure value that compresses the oil (favoring the recovery of a defined volume since the oil is compressible, being in mixture with gaseous components) and which causes a mechanical expansion of the casing of the transformer.

A first performance indicator characteristic of the structural behavior of the casing is formed by the curve of flexibility in the static regime, i.e. the curve that expresses the increase of volume of the enclosure as a function of a static internal overpressure. The curve of flexibility of the container of the transformer in question was calculated using finite element analysis to accurately conduct, through a structural model of the tank of the transformer which has reproduced the characteristics of the materials of the body and the geometric and reinforcement ones, as well as those of the systems of clamping of the cover. Applying to the above-mentioned model a progressively increasing pressure, the deformation of the casing is obtained as elastic and elastoplastic response and, therefore, the additional volumes made available as a result of its expansion until it reaches a condition of breakage. In the left part of Figure 1 (a) below shows the characteristic deformation (expansion in volume) pressure of the casing of the transformer in question, in its real geometry and constructive realization; in the right part of Figure 1 (b) below, instead, it shows the maximum deformation in relation to the internal pressure.

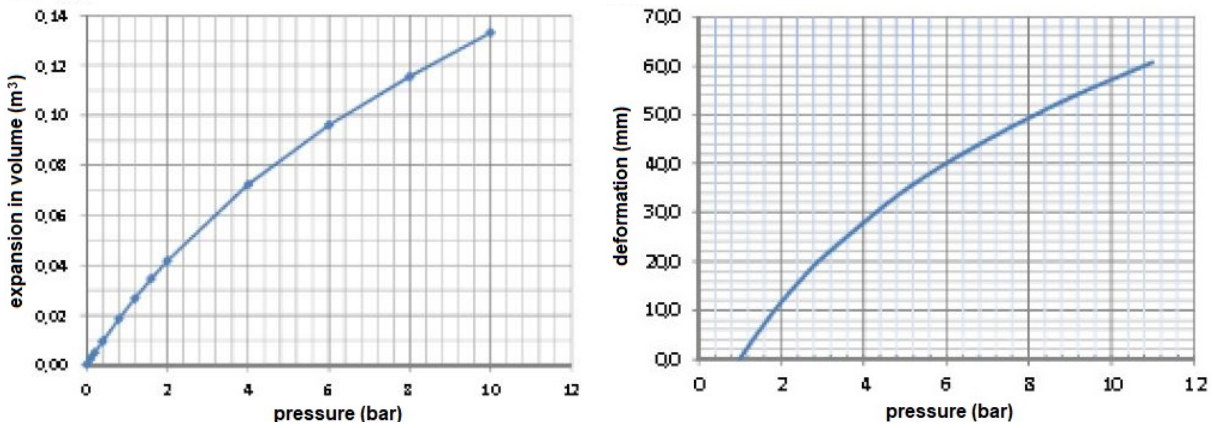

Figure 1.

a)

The change in the volume (m^3)

of the casing of the transformer

as a function of the internal pressure

b)

The deformation (mm)

of the casing of the transformer

as a function of the internal pressure

It is clear that already at pressures of values limited to 4-5 bar, as already noted in the previous Chapter 4, the deformations of the transformer are such as to justify the outflow of the oil. For the calculation of the equilibrium pressure, this report employs two models. The first considers the oil incompressible as if he had gaseous components in the mixture: this model is more common in literature and featured a simpler mathematical formulation. A second model, however, considers the presence of gaseous species within the oil and has been specifically developed for this analysis. In this case, it has been considered the above equation (8) as a relation of compressibility and a formulated solution of the model iterative, of greater complexity. As already noted, the compressibility of the oil, making available physical

volumes as the pressure increases, leading to the value of equilibrium pressure lower than those that occur when the oil has a lower compressibility (virgin oil).

2.1.3 First model: incompressible oil

The compressibility of the oil is in first approximation, neglected in the literature, being several orders of magnitude lower than that of the gas and that of the values of flexibility typical of common casings of the transformers, including those armored. In the present analysis it was considered infinitely rigid oil for which the initial volume does not change following the events. All changes in the volume that are generated as a result of pyrolysis must be compensated by the change in volume of the enclosure of the transformer. The gas formed, then, follow the typical changes that characterize them, in respect of energy conservation. The pressure-volume behavior of the gas generated by pyrolysis is given by its state equation in the form:

$$p \cdot V = n_{mol} \cdot R \cdot T \tag{15}$$

where: "n" is the number of moles produced, "R" the universal constant of perfect gases, "T" the formation temperature of the pyrolysis gas; the volume "V" that appears in (15) is that of the gas that is generated. The temperature "T" can be expressed in terms of the energy released by the arc in accordance with the principle of conservation of energy for closed systems. The latter expresses that:

$$\Delta U = c_0 \cdot M_{pyrolisis\ gas} \cdot \Delta T \cong c_0 \cdot M_{pyrolisis\ gas} \cdot T$$

while the first term can be matched to the energy of the arc participating in the pyrolysis process:

$$\Delta U = E_a \tag{16}$$

With this hypothesis it is assumed that all the energy of arc participates in the pyrolysis process: this in favor of a prediction that enhances the process of pressurization of the oil, in the sense of providing a data that certainly overestimates the real situations. This partially compensates the uncertainty that we have on the rate of formation of pyrolysis gas, in accordance with what is already observed. For the temperature we have:

$$T \cong \frac{E_a}{c_v \cdot M_{pyrolisis\ gas}} \tag{17}$$

and this report, substituted in the equation of state of perfect gases, provides:

$$p \cdot V = n_{mol} \cdot R \cdot \frac{E_a}{c_v \cdot M_{pyrolisis\ gas}} = \frac{n_{mol}}{M_{pyrolisis\ gas}} \cdot \frac{R}{c_v} \cdot E_a = \frac{R}{PM} \cdot \frac{E_a}{c_v} =$$

$$= R_{pyrolisis\ gas} \cdot \frac{E_a}{c_v} = \frac{c_p - c_v}{c_v} \cdot E_a \tag{18}$$

And then to the definitive:

$$p \cdot V = (k-1) \cdot E_a \tag{19}$$

This equation in the plane "pV" (pressure-volume) represents a set of hyperbolas (defined hyperbola energy of the pyrolysis gas) that can be specified is fixed when the term "Ea" (as previous considerations). The expression (19) can be written highlighting the rate of pyrolysis gas formed (per unit of energy of the arc) and the same arcing energy in the form:

$$p \cdot V = c_1 \cdot (k-1) \cdot E_a \cdot \nu_L \tag{20}$$

being "c_1" a constant that allows the expression "ν_L" in l/kJ*arc in standard or normal conditions and "E_a" in MJ, according to a widespread tradition of industry. It is evident that equation (20) adds nothing as phenomena: it is preferred to refer to it as it allows to enter data ("ν_L" and "E_a") that are currently expressed in l/kJ*arc and MJ. The underlying Figures 2, 3 and 4 shows hyperboles obtained by adopting a production rate of gas equal to: 0.05 l/kJ*arc; 0.1 l/kJ*arc and 0.2 l/kJ*arc (under normal conditions). The intersection between the following Figures 2, 3 and 4 and the previous Figure 1 provides, in the three cases proposed, the equilibrium pressures within the transformer.

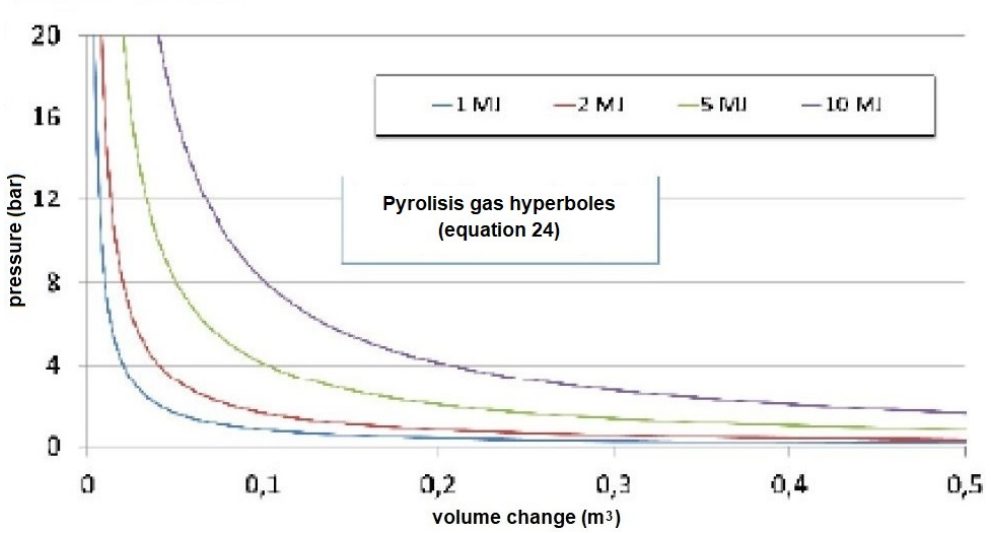

Figure 2. Hyperbole of the energy related to pyrolisis gas (V_L = 0,05 l/kJ $_{arc}$)

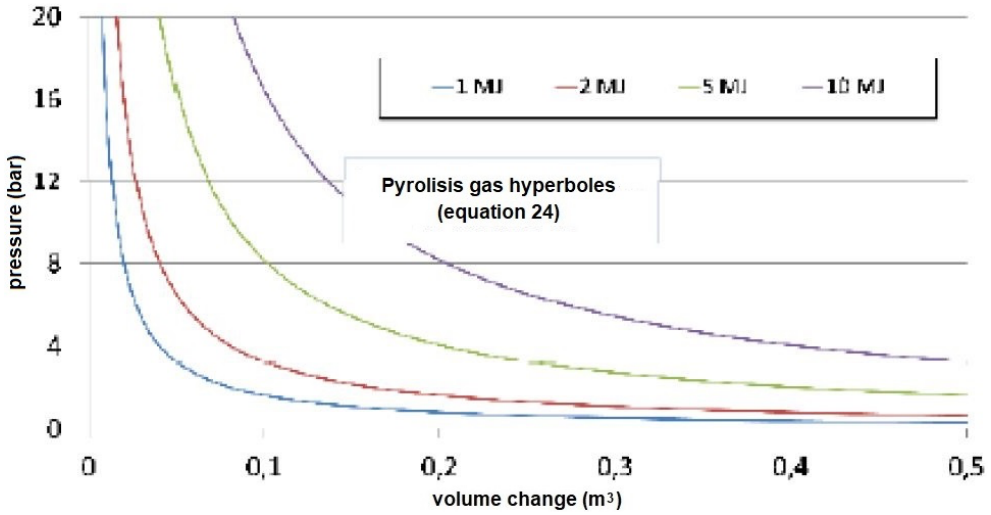

Figure 3. Hyperbole of the energy related to pyrolisis gas (V_L = 0,1 l/kJ $_{arc}$)

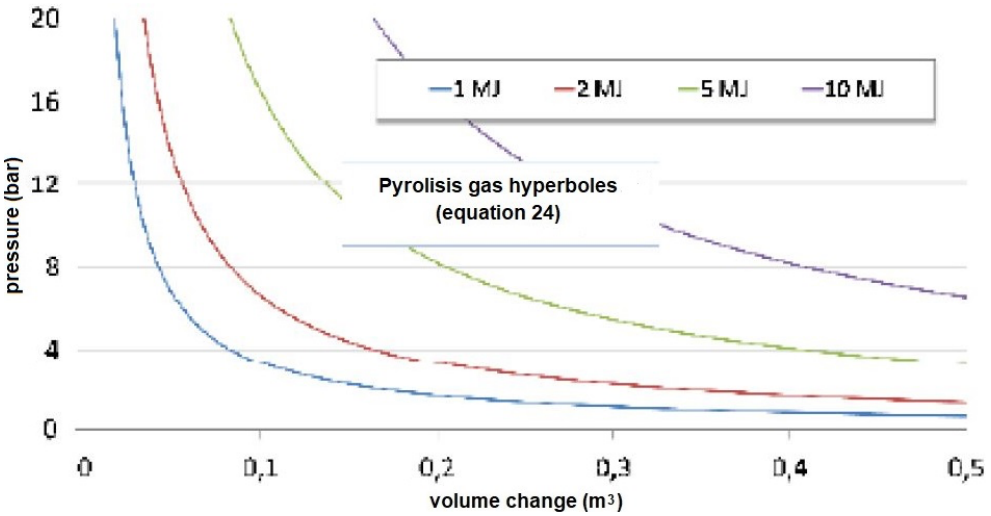

Figure 4. Hyperbole of the energy related to pyrolisis gas (V_L = 0,2 l/kJ $_{arc}$)

They correspond to the solution of:

$$\frac{(k-1)\cdot E_a}{p} = \Delta V_{transformer\ casing} = f(p) = a\cdot p^2 + b\cdot p + c \qquad (21)$$

where the constants were determined by interpolation of the data shown on the left side of the previous Figure 1. The result:

$$\Delta V_{transformer\ casing} = -8\cdot 10^{-3}\cdot p^2 + 22.1\cdot 10^{-3}\cdot p^{-0.02} \qquad (22)$$

For convenience of consultation, the results are reported below in Figures 5, 6 and 7, proposals on the following page.

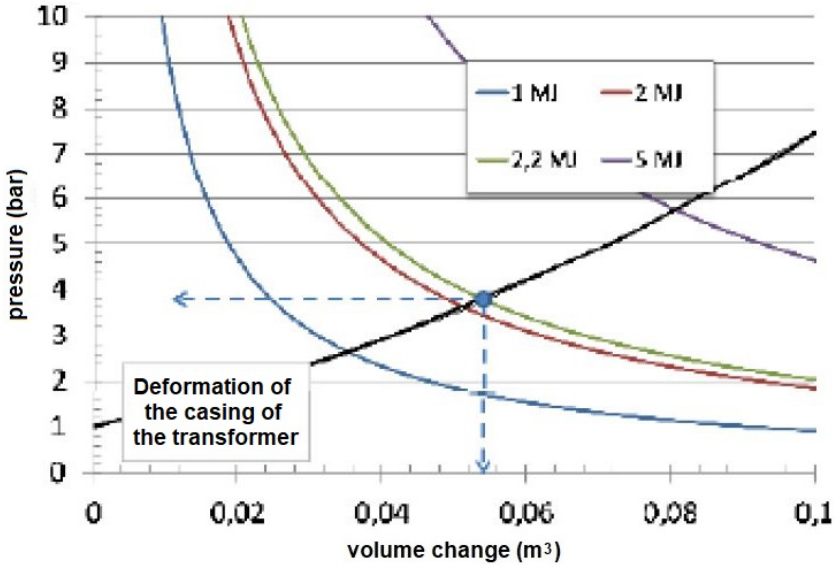

Figure 5. Equilibrium pressures between the casing of the transformer and the hyperbole of the energy related to pyrolisis gas (V_L = 0,05 l/kJ $_{arc}$)

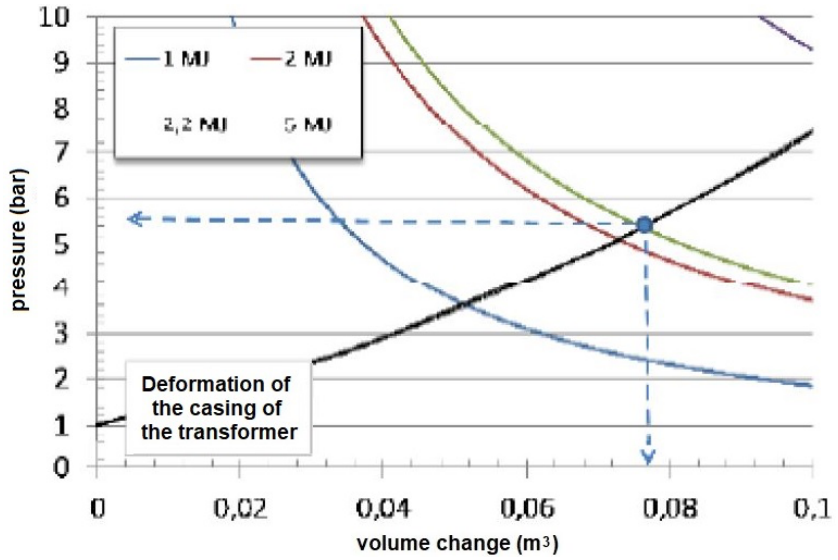

Figure 6. Equilibrium pressures between the casing of the transformer and the hyperbole of the energy related to pyrolisis gas (V_L = 0,1 l/kJ $_{arc}$)

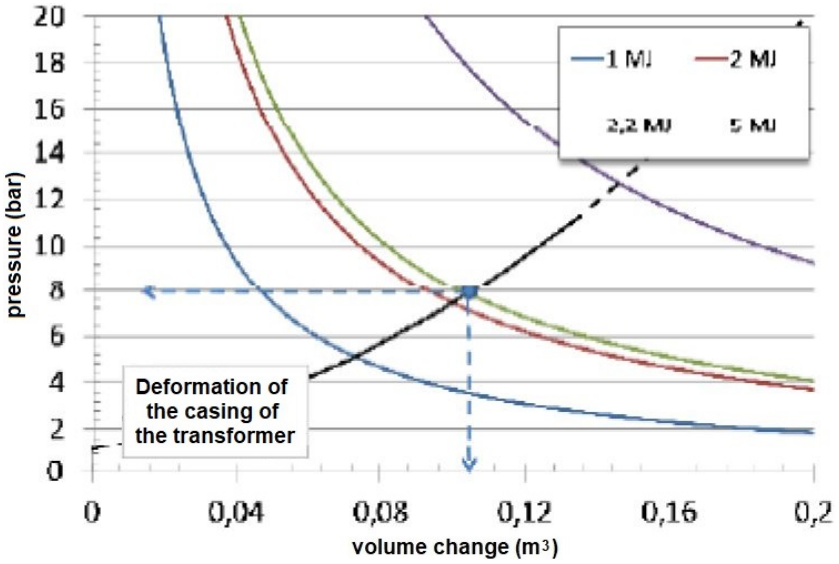

Figure 7. Equilibrium pressures between the casing of the transformer and the hyperbole of the energy related to pyrolisis gas (V_L = 0,2 l/kJ $_{arc}$)

In the first case, the equilibrium pressure is equal to 3.8 bar; in the second case equal to 5.6 bar; in the third case equal to about 8 bar. These data lead back the analysis to a formal correctness and values that are typical of the phenomena under examination. It is necessary to recall from literature data, that the overpressure dynamics can be estimated on average equal to 50% compared to the data given. The observation of the right part of the previous Figure 1 shows that significant deformations of the casing, which no longer ensure its oil proof, correspond already to the relative pressure values. The figure shown does not consider energy losses between the manifestation of the arc and the phenomenon of pyrolysis: therefore, the results are considered overestimated than the real situation. Even in the compressibility of the oil, the event pressurizing the oil has not been particularly intense: it is clear testimony to the limited amount of oil that has been ejected from the amount (initially) contained in the transformer.

2.1.4 Second model: compressible oil

This second model considers the compressibility of the oil as it mixed with gas generated in relation to the use of the transformer. As noted, this analysis represents a more than found in literature; here just done to evaluate the effect of the quality of the oil, relatively to the gaseous inclusions, on the equilibrium pressure downstream of the phenomenon of electric discharge. The model in this case is much more complex in that, following a defined value of equilibrium pressure, become available in the following volumes:

a) the volume produced by the pyrolysis gas given by:

$$\Delta V' = \frac{(k-1)\cdot E_a}{p} \tag{23}$$

which, as said, is a function of the energy of arc and the rate of pyrolysis gas produced per unit of energy of the arc;

b) the volume of which is contracted the mixture oil-dissolved gases given by:

$$\Delta V'' = \frac{V_{in}}{\beta_{mix}}\cdot p = \frac{V_{in}}{\beta_{oil}\cdot\dfrac{1+\dfrac{V_{gas}}{V_{oil}}\cdot\left(\dfrac{p_a}{p_a+p}\right)^{\frac{1}{k}}}{1+\dfrac{V_{gas}}{V_{oil}}\cdot\dfrac{(p_a)^{\frac{1}{k}}}{k(p_a+p)^{\frac{k+1}{k}}}\cdot\beta_{oil}}}\cdot p \tag{24}$$

which depends on the volume percentages of the gases within the mixture, the dissolved substances and the ratio "k" between the values of specific heats at constant pressure and volume;

c) the volume made available by the expansion of the transformer tank for elasto-plasticity, according to the equation already given in (25) and below revived ready for abutment:

$$\Delta V_{transformer\ casing} = -8 \cdot 10^{-3} \cdot p^2 + 22.1 \cdot 10^{-3} \cdot p^{-0.02} \quad (25)$$

The equilibrium is reached when determining a pressure value which cancels the following equation:

$$\Delta V' - \Delta V'' - \Delta V_{transformer\ casing} = 0 \quad (26)$$

$$\frac{(k-1) \cdot E_a}{p} - \frac{V_{in}}{\beta_{oil} \cdot \frac{1 + \frac{V_{gas}}{V_{oil}} \cdot \left(\frac{p_a}{p_a + p}\right)^{\frac{1}{k}}}{1 + \frac{V_{gas}}{V_{oil}} \cdot \frac{(p_a)^{\frac{1}{k}}}{k(p_a + p)^{\frac{k+1}{k}}} \cdot \beta_{oil}}} \cdot p - 8 \cdot 10^{-3} \cdot p^2 + 22.1 \cdot 10^{-3} \cdot p^{-0.02} = 0 \quad (27)$$

The above equation (27) resolved in an iterative manner provides the actual pressure inside the transformer for arcing energy equal to that of the event really occurred, to vary the percentage of dissolved gases and the chemical composition of the same. This new value of pressure is always lower than that deduced from the condition of oil incompressible. The pressure difference is shown in the below Figure 8 for various percentages of gas (acetylene) dissolved in the oil, to vary the rate of gas produced by the pyrolysis reaction.

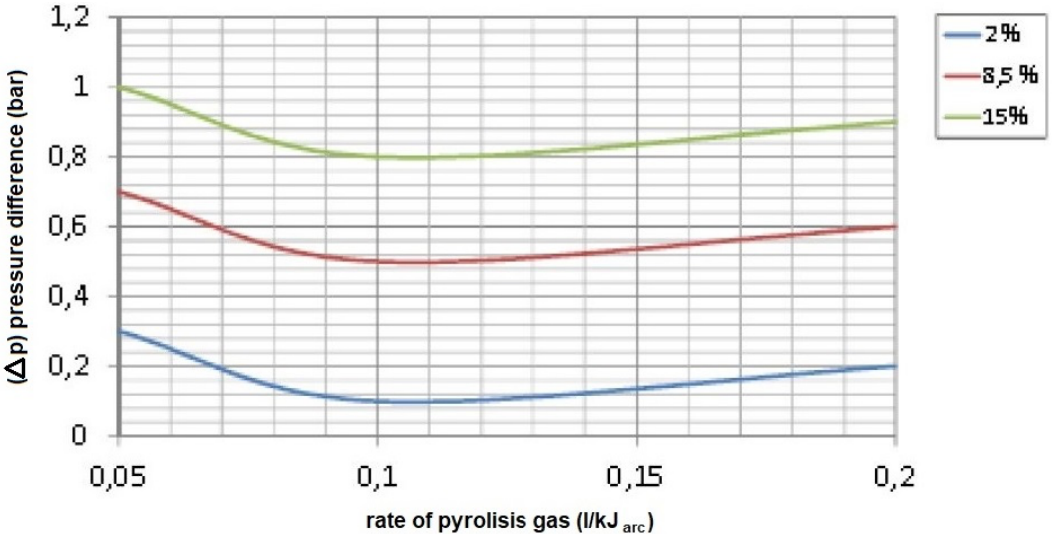

Figure 8. The decrease in pressure inside the transformer related to gas dissolved in the oil

As already noted, the correction poses a transformer with dissolved gas inside, under conditions of greater structural safety in the presence of a phenomenon of arc: with increasing of dissolved gases, increases the pressure difference between the case of oil not compressible and the real one. In the case of a concentration equal to 8.5% by volume of acetylene, and most likely at a rate of 0.1 l/kJ*arc, the pressure decreases of 0.5 bar, bringing the equilibrium value equal to about 5 bar (Figure 6). The inclusion of a factor that takes into account the dynamic effects related to the extreme rapidity of the phenomenon of generation of pyrolysis gas and of transmission of pressure waves equal to 1.5, in agreement to the literature of the field (as noted above), would lead the value of said pressure to about 7-8 bar.

3. CONCLUSIONS

Here, for convenience of reference, we refer to some notes as summary of the calculation of the pressure inside the transformer being accidental event, due to the manifestation of an electrical arc inside. The problem is well known and has required the development of a method that is widely reflected in the technical scientific literature: given the complexity of the phenomena involved and the uncertainty relevant to different sizes, many of which are also not deterministic, prompted an indispensable reference to literature about, in order not to give rise to doubts of validity. The study carried out and reported in this document, and the observation of some comparative results of the events occurred let you see how outlined below.

1) The power that characterized the phenomenon of the arc was about 10 MW. The electrical arc that is generated has been classified as a high power to the power class of the transformer in question and the energy released is also defined as high, able to develop a "bubble" gas, about 220 liters, therefore equal to a quarter of the volume of the entire container (housing) of the transformer under exam, which is also, therefore, quantitatively very significant. Such a phenomenon is of such intensity to let think of a specific event, abnormal and not predictable, of particular gravity, most probably caused by external factors not related to the daily exercise of the transformer (such as, for example, the quality of the oil). The gases dissolved in the oil, as a result of normal operation, could certainly give a result of a phenomenon of electric discharge, as is normally the case with microdischarges and content phenomena that progressively deplete the ability of the oil to maintain adequate dielectric capacity, but not so intense as that occurred. Nor is there evidence of events that leave thinking about a rapid decline of oil properties. As reflected in the above, the possibility of breakage of the bar insulation controller (drive) voltage, to external factors, it is certainly capable of triggering a sequence of localized events and earnings, as might suggest a degeneration of oil, capable of generating an arc of considerable electric intensity which one it had on the occasion of known event. A further support to this hypothesis is the strong localization of the outcomes of the contact of a short circuit that has been generated within the transformer, which reveals the presence of a phenomenon prevalent than the other which subsequently can be occurred.

2) The state of the oil inside the transformer does not increase the pressure that is generated inside the transformer (in the tank) as a result of the electrical arc, rather attenuates it: the percentage of dissolved gas present at the time of electric discharge plays a role as to make the instantaneous overpressure generated less severe. The gases dissolved in the oil, because of the aging of the same, make the mixture of oil and gas more compressible: this situation provides a useful volume, when the pressure increases, to the gases that are generated as a result of the pyrolysis process and the increase of the total pressure remains more content. At the concentration of acetylene of the order of 8.5%, which are detected in the real case in question, the effect of the compressibility of the oil reduces the pressure by about 10% compared to the pressure value which would occur in the absence of dissolved gases.

3) The presence of dissolved gases in the oil cannot have aggravated the energy released during or as a result of the electrical discharge and, therefore, does not have aggravated the accident event. The presence of combustible gases in the oil, in fact, certainly has not generated the processes of combustions or secondary oxidations inside the enclosure of the transformer due to the absence of oxidizing agents. At the outflow of the oil through the opening of the lid cannot be excluded a process of secondary oxidation (pool fire) also not macroscopic, but such a process at the time where occurred, after the verification of the event of the arc, it is to be considered inevitable.

4) The overpressure that is generated inside the transformer is much less intense than it would be if we had taken the real and simplifying incorrect assumption of a container infinitely rigid: the overpressure calculation shows that with high probability are around 7.5 bar and, anyway, such as to justify the leakage of the pressurized oil to deformation of the structure and loss of containment capability. This conclusion is the result of a complex model that considers the elasto-plastic deformation of the casing of the transformer broken, not negligible, as well as of the dynamic effects related to the rapidity of the phenomena, considered such as aggravation of the equilibrium pressure that comes from the calculation model by a factor of 1.5.

5) The presence of dissolved gases in the oil makes the phenomenon of propagation of the disturbance of less impulsive pressure from the time it triggers the pressure wave resulting from the pyrolysis oil. The times of propagation of the pressure wave, in fact, significantly increase (by a factor of 2-3) and this acts in the direction of the structural integrity of the casing, allowing the pressurization of the gases dissolved and, hence, reduction of pressure increase as an outbreak occurs.
6) The periodic oil maintenance does not affect in the phenomenon.

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